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Evaluation of silicon nitride reinforced silica aerogel composites for radom application

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Abstract

Thanks to its lightness and superior mechanical properties, advanced technology composite materials have a wide range of use in aviation, not only in interiors, but also in the production of structural parts. The radom in the nose of the aircraft is one of the areas of use of advanced technology composite materials. Silica aerogels with high specific surface area (500–1200m^2/g), low density (approx. 0.003–0.5 g/cm^3), low thermal conductivity (0.005–0.1 $Wm^{-1}K^{-1}$), ultra-low dielectric constant (1.0–2.0) and low dielectric loss (10^{-2} – 10^{-4}) are potential materials for use in radom application. Recently, with the rapid development of aviation technologies, the speed of aircraft has improved significantly. This situation revealed the necessity of increasing the high temperature performance of silica aerogel radomes. Silicon nitride is a promising structural-functional reinforcement phase for silica aerogel radomes due to its excellent thermo-mechanical and dielectric properties. In this study, studies and results of silica aerogel composites reinforced with Si_3N_4 are presented and discussed.

Introduction

The radomes part of the nose of the aircraft is one of the areas of use of advanced technology materials (Figure 1). The radom is the structure used to protect the antennas from the effects of the outside world. It is an electrically transparent material to electromagnetic energy, where power loss in transmission must be minimal. Therefore, the dielectric constant and loss tangent of the material significantly affect the conduction loss. Radomes have walls separated by a core, as in a solid wall or sandwich structure. The wall configuration of the radom varies according to the application areas. One of the radom types is a graduated porous structure where the porosity lowers the dielectric constant and thus has high power transfer efficiency. This layer can be damaged by moisture due to its porous structure. Radomes are produced from dielectric materials in a way that will least affect the electromagnetic performance of the antennas they contain. In addition, the permeability of radom is often inversely related to its mechanical strength. Carbon has detrimental effects on radom performance because it absorbs electromagnetic radiation and water has a high dielectric constant relative to the radom material itself. The dielectric constant and loss tangent of the material also affect the transmission loss during electromagnetic radiation. In addition to low dielectric constant and loss, high strength, high thermal shock resistance and high thermal stability are the desired basic properties [1].

In radomes, engineering plastics such as glass fiber reinforced epoxy, or ceramic-based composites are used, especially in radomes that will be exposed to high temperatures. The general use temperatures of glass fiber reinforced composites are below 147 °C. In addition, low modulus of elasticity and compressive strength are other factors limiting their use in aviation. The low modulus of elasticity causes excessive stress in the plastic matrix, which causes fractures when stress is applied, thus shortening the fatigue life. Therefore, there is a need for materials that will show high performance, especially at high temperatures [1].

Figure 1. Representation of the radom in the nose of the aircraft [2]

Radomes should be made of materials that can protect internal electronic equipment from high temperatures, are wave-transparent and provide thermal insulation. Silica aerogels with high specific surface area (500–1200m^2/g), low density (approx. 0.003–0.5 g/cm3), low thermal conductivity (0.005–0.1 Wm-1 K-1), ultra-low dielectric constant (1.0–2.0) and low dielectric loss (10^{-2} – 10^{-4}) are potential materials for use in this field [3-4-5]. Aerogels are mostly used in the field of thermal insulation due to their low thermal conductivity values, and there are many studies on this subject [6]. However, these applications are limited to non-bearing structures due to fragility [7-8]. Therefore, great efforts are made to produce high-strength aerogel [9]. The incorporation of ceramic fiber into the aerogel not only improves the mechanical properties, but also reduces the radiative heat transfer of the aerogel at high temperature, making it possible to use the aerogel as a load-bearing insulation material as a Thermal Protection System (TPS). It is important to examine the creep behavior of aerogel composite insulation materials with load bearing capacity.

Recently, with the rapid development of aviation technologies, the speed of aircraft has improved significantly. This situation revealed the necessity of increasing the high temperature performance of radomes. Silica aerogels can be used as a radom due to the above-mentioned properties; but their strength is low. In addition, the mesoporous structure of silica aerogels deteriorates above 800^{o}C and the thermal insulation performance deteriorates. It has been reported in the literature that silica aerogels with a density of 0.12 g/cm^3 deteriorate under a stress of 31 kPa [10]. In addition, although cross-linked polymer aerogels are suitable for this field, their use is limited in high temperature applications due to thermal pyrolysis of the polymer above 800°C.

To overcome these problems, it is necessary to improve the strength and thermal stability of silica aerogels. There are some methods are reported in literature: Structural strengthening [11-12-13], fiber reinforcement [9, 14-15], polymer crosslinking [16-17-18] or chemical/physical strengthening [19-20-21] procedures have been reported in the literature. Silicon nitride is a promising structural-functional material for radomes due to its excellent thermo-mechanical and dielectric properties [22-23-24-25-26]. By adding Si_3N_4 particles into the aerogel matrix, it is possible to improve the termo-mechanical properties while maintaining low dielectric constant and low dielectric loss properties.

Si_3N_4 Reinforced Silica Aerogel Composites

In the literature, there are limited studies on the production of Si_3N_4 reinforced silica aerogel composites [27].

Si_3N_4 particle reinforced silica aerogel composites were produced by sol-gel method by drying at ambient pressure by Yang et al. [16]. The microstructure, thermal insulation, mechanical and dielectric properties of the composites were investigated. The effect of the amount of Si_3N_4 (0, 2, 5, 10, 15,20 vol%) on the microstructure and properties is explained. The obtained mesoporous composites were found to have low thermal conductivity (0.024–0.072Wm^{-1} K^{-1}), low dielectric constant (1.55–1.85) and low dielectric loss (0.005–0.007). As the Si_3N_4 content increased from 5% to 20% by volume, the compressive strength and flexural strength of the composites increased from 3.21 to 12.05MPa and 0.36 to 2.45MPa, respectively. It has been reported that the obtained composites show significant promise in radom applications with the functional integration of wave transparency and thermal insulation. High temperature properties and interface evolution of Si_3N_4 fiber reinforced silica matrix wave transparent composite materials were investigated by another research group [16]. Here the matrix is silica, not aerogel. In the study, Si_3N_4 fiber reinforced silica matrix composites were produced by using the sol-gel method together with the filament winding method in order to improve the high temperature performance of wave transparent materials for high speed aircraft applications. The mechanical properties and interfacial development of the composites at high temperatures were investigated. The properties were evaluated by sintering the composites in two different furnace atmospheres (air and nitrogen). The results showed that composites sintered in a nitrogen atmosphere retained a flexural strength of 210 MPa up to 1200°C, while their air-prepared counterparts held up to approximately 73 MPa. In another study [27], Si_3N_4 particles embedded in the nano-network of silica aerogel prevent aerogel crystallization at high temperatures, thus increasing the strength. In order to reduce the radiative thermal conductivity, it is additionally doped with the opacifier TiO_2. TiO_2 containing Si3N4/SiO2 aerogel composites were heat treated at 900, 1100, 1200 and 1300 °C for 2 hours. The schematic production process flow chart of the TiO_2 incorporated Si_3N_4/SiO_2 aerogel composites were given in Figure 2.

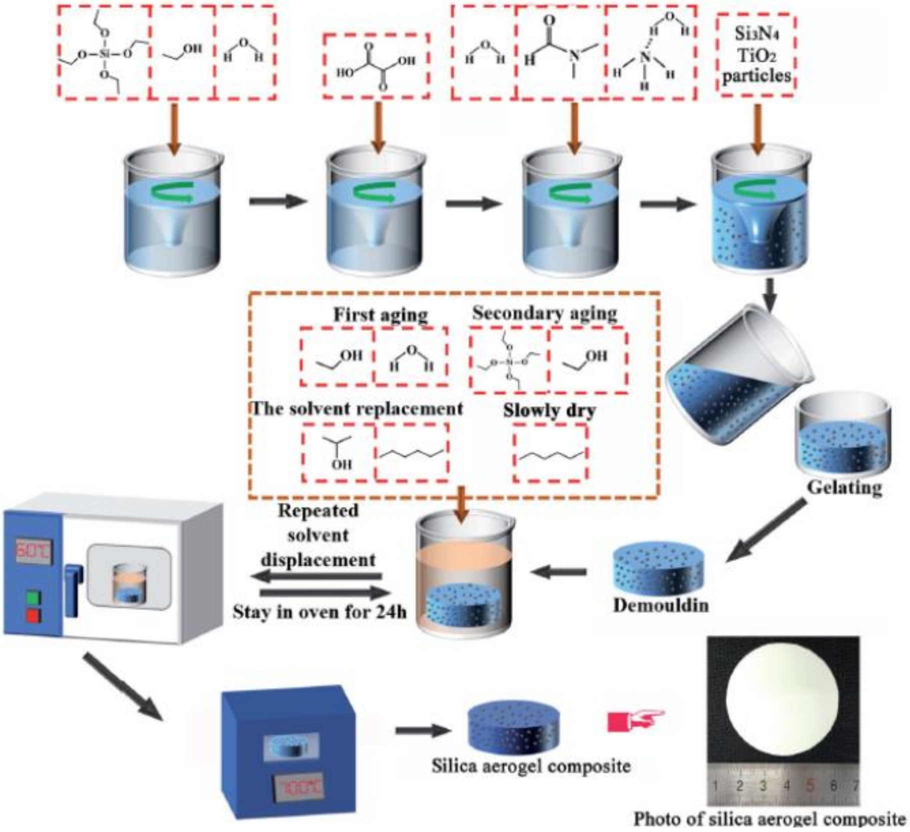

Figure 2. Schematic image of the sample preparation process [27]

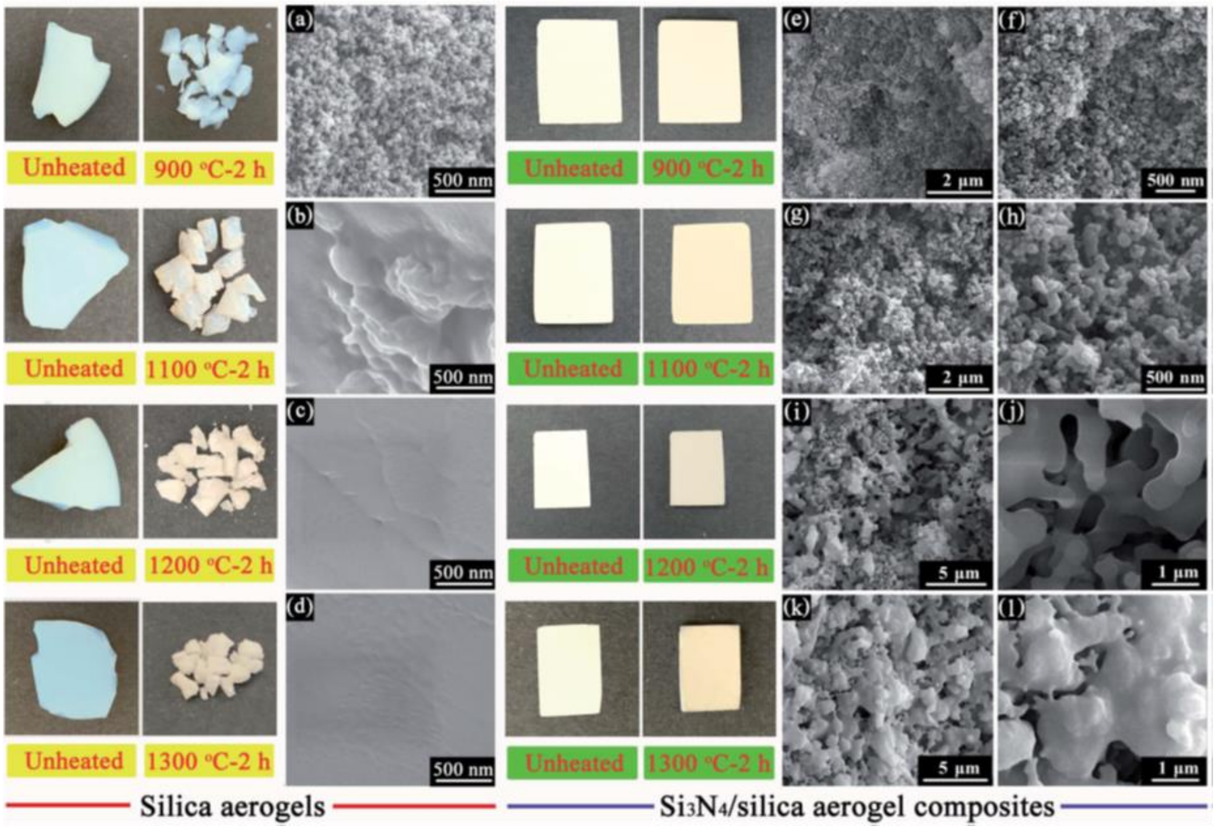

Figure 3. Photographs and SEM images of Si_3N_4-aerogel composite samples heat treated at different temperatures before and after heat treatment [27]

Photographs and SEM images of TiO_2 incorporated Si_3N_4-aerogel composite samples heat treated at different temperatures before and after heat treatment are shown in Figure 3. As seen from the images, after the heat treatment at 900 °C, the pure aerogel sample is brittle. At higher heat treatment temperatures, the silica aerogel within the composite material gradually crystallizes, and the fusion of micro pores causes pore shrinkage and increase in pore size. After heat treatment at 1300 °C, Si_3N_4 particle reinforced composites remained intact without cracks. Si_3N_4 particle addition increased the strength.

Conclusion

When the limited studies in the literature are evaluated, the addition of Si_3N_4 improves the thermo-mechanical properties of silica aerogels. However, there is a need for new production techniques that can be produced on a pilot/large scale so that Si_3N_4 reinforced silica aerogel composites can be used commercially in radom applications.

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